Climate Variability in Ocean Surface Turbulent Fluxes

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1. PROJECT SUMMARY

FSU produces fields of surface turbulent air-sea fluxes and the flux related variables (winds, SST, near surface air temperature, near surface humidity, and surface pressure) for use in global climate studies. Surface fluxes are by definition rates of exchange, per unit surface area, between the ocean and the atmosphere. Stress is the flux of horizontal momentum (imparted by the wind on the ocean). The evaporative moisture flux would be the rate, per unit area, at which moisture is transferred from the ocean to the air. The latent heat flux (LHF) is related to the moisture flux: it is the rate (per unit area) at which energy associated with the phase change of water is transferred from the ocean to the atmosphere. Similarly, the sensible heat flux (SHF) is the rate at which thermal energy (associated with heating, but without a phase change) is transferred from the ocean to the atmosphere. In the tropics, the latent heat flux is typically an order of magnitude greater than the sensible heat flux; however, in the polar regions the SHF can dominate.

The FSU activity is motivated by a need to better understand interactions between the ocean and atmosphere on weekly to interdecadal time scales. Air-sea exchanges (fluxes) are sensitive indicators of changes in the climate, with links to floods and droughts[1] and East Coast storm intensity and storm tracks[2]. On smaller spatial and temporal scales they can be related to the storm surge, and tropical storm intensity. On longer temporal scales, several well-known climate variations (e.g., El Niño/Southern Oscillation (ENSO); North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO)) have been identified as having direct impact on the U.S. economy and its citizens. Improved predictions of ENSO phase and associated impact on regional weather patterns could be extremely useful to the agricultural community. Agricultural decisions in the southeast U.S. sector based on ENSO predictions could benefit the U.S. economy by over $100 million annually[3]. A similar, more recent estimate for the entire U.S. agricultural production suggests economic value of non-perfect ENSO predictions to be over $240 million annually[4]. These impacts could easily be extended to other economic sectors, adding further economic value. Moreover, similar economic value could be foreseen in other world economies, making the present study valuable to the global meteorological community.

ENSO, PDO, and NAO (AO) each have atmospheric and oceanic components that are linked through the surface of the ocean. Changes in the upper ocean circulation result in modifications

[1] Enfield, D. B., A. M. Metas-Nuñez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophy. Res. Let.*, **28**, 2077-2080.

[2] Hurrell, J.W., and R.R. Dickson, 2004: Climate variability over the North Atlantic. Marine Ecosystems and Climate Variation - the North Atlantic. N.C. Stenseth, G. Ottersen, J.W. Hurrell, and A. Belgrano, Eds. Oxford University Press, 2004.

[3] Adams, R. M., K. J. Bryant, B. A. McCarl, D. M. Legler, J. O'Brien, A. Solow, and R. Weiler, 1995: Value of improved long-range weather information. *Contemporary Economic Policy*, **13**, 10-19.

[4] Solow, A. R., R. F. Adams, K. J. Bryant, D. M. Legler, J. J. O'Brien, B. A. McCarl, W. Nayda, and R. Weiler, 1998: The value of improved ENSO prediction to U. S. agriculture. *Climate Change*, **39**, 47-60.

to the SST and near surface wind patterns. Variations in SSTs can be related to ENSO and other climate patterns; however, it is the fluxes of heat and radiation near the ocean surface that transfer energy across the air-sea interface. It is an improved understanding of these turbulent fluxes and their variability that motivates our research (radiative fluxes are difficult to accurately estimate from in situ data; however, satellite-based estimates are available). By constructing high quality fields of surface fluxes we provide the research community the improved capabilities to investigate the energy exchange at the ocean surface.

FSU produces both monthly in-situ based (the FSU3) and hybrid satellite/numerical weather prediction (NWP) fields of fluxes and the flux-related variables. Our long-term monthly fields are well suited for seasonal to decadal studies, and our hybrid satellite/NWP fields are ideal for daily to annual variability and quality assessment of the monthly products. The flux-related variables are useful for ocean forcing in models, testing coupled ocean/atmospheric models, and for understanding climate related variability (e,g., the monthly Atlantic surface pressure is a good indicator of extreme monthly air temperatures over Florida).

The flux project at FSU targets the data assimilation milestones within the Program Plan. Our assimilation efforts combine ocean surface data from multiple Ocean Observing System networks (e.g., VOS, moored and drifting buoys, and satellites). One set of performance measures targeted in the Program Plan is the air-sea exchange of heat, momentum, and fresh water. When the FSU products are combined with ocean models (either at FSU or other institutes), performance measures relating to surface circulation and ocean transports can be addressed. The FSU flux project also focuses on the task of evaluating operational assimilation systems (e.g., NCEP and ECMWF reanalyses) and continues to provide timely data products that are used for a wide range of ENSO forecast systems. All products are distributed in a free and open manner at: http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/.

2. ACCOMPLISHMENTS

An analysis of nine flux products (including the FSU Fluxes) has been completed, and it has revealed a vast difference between these products. We have updated this analysis, and improved our understanding of key differences among these products. We have nearly completed production of research-quality, in-situ monthly flux fields for the tropical and North Pacific Ocean (1978 to 2004). In the previous year, we identified some problems that result in unrealistic fields around the TAO moorings (a similar problem was identified in many of the comparison products); this year we solved this problem in our FSU3 product. The product release of the Pacific product has been delayed until we can complete the editing of the winds, which are key components in the fluxes.

We also continued our operational production of monthly quick-look wind fields for the tropical Pacific and Indian Oceans. These are based on our older techniques.

Global and Regional satellite wind and stress products have continued to improve through minor improvements in our variational technique. We have greatly lengthened the time series of this data set. We have also examined the biases in fluxes due to ignoring sub-monthly variability, and found these to be physically important >5 Wm^{-2} over the vast majority of the world's oceans, including the tropics! In high-latitude winters, monthly averaged biases often exceeded 30Wm^{-2}. In most cases, these biases were associated with the passage of atmospheric fronts, and the highly correlated changes in air temperature, atmospheric humidity, and wind speed. Our gridding technique for the monthly in situ data handles these issues very well for stress, but does not do so for heat fluxes (nor could any similarly derived monthly average). We had hoped to use NWP air temperature and humidity, combined with satellite winds to solve this problem; however, we found that temperature and humidity changes associated with frontal passages were not well resolved in NWP products, making useful bias adjustments very difficult if not impossible. Unfunded work with collaborators suggests that air temperatures and humidities estimated from satellite observations could do better, but it is not clear if the sampling is sufficient to reduce the biases below a few Wm^{-2}.

The effective reduction in funding (level funding combined with increasing costs) has prevented us from working on the error analysis for our fields. We view this work as very important, but we lack the resources to continue that effort with our current budget. We are participating on other efforts that will help address key questions about the noise and practical resolution. That will be very helpful, but a spatially varying assessment is desired.

Deliverables for FY 2008 included:

1. Update Atlantic, Indian, and Pacific Oceans using new ICOADS releases (if available).
2. Complete Equatorial and North Pacific 1° winds and fluxes.
3. Begin operational production and distribution of quick-look, 1° in situ fluxes for the Atlantic, Indian, and Pacific Oceans.
4. Publish comparisons of FSU3 fluxes to other available in-situ, satellite, and blended flux products.
    - Subtask1: Report results at national and international meetings.
5. Objective estimation of uncertainty in flux fields and related variables.
    - Subtask1: First complete uncertainties for wind vector components.
6. Production of satellite and NWP hybrid fluxes.
    - Subtask1: Estimate biases in NWP near surface temperatures and humidities.
    - Subtask2: Assess the importance of height adjustment algorithms for humidity (preliminary results indicate that this can be a large difference).
    - Subtask3: Assess biases associated with ignoring short-term variability contributing to surface fluxes.

2.1. Update products using new ICOADS releases [Deliverable 1]

No updates for ICOADS were made available in FY 2008; therefore, we did not complete any updates or extensions to our products past 2004. We anticipate an ICOADS update to be released in 2009, so this task will be pushed forward.

2.2. Complete Equatorial and North Pacific 1° in-situ fluxes [Deliverable 2]

In FY 2008, we nearly completed the automated and visual data quality evaluation for the tropical and North Pacific Ocean fluxes for the period 1990-2004. We completed the scalar input fields (wind speed, air temperature, and atmospheric humidity) for 1978 to 2004, and have edited the wind vectors for 1982 through 2004 (leaving on 1978 through 1981 to be completed). The 1˚ wind and flux products (the FSU3) for the Pacific Ocean revealed a problem with our handling of moored buoys (especially in the tropics) which resulted in the mooring chains being evident in the objective flux fields. The problem is due to the sparse longitudinal sampling of the TAO buoys, and to small but widespread and seasonally varying biases relative to the ship observations. The treatment of buoy data has been modified to remove this problem in a manner that retains most of the value of the buoy data. In 2007, we found that many ship observations had been misclassified (in ICOADS) as moored buoys. We have developed an automated technique for removing the vast majority of such misclassified data, and found a small positive impact to the flux fields, and more substantial reduction in the questionable data removed in the editing process.

2.3. Production of in-situ quick-look products [Deliverable 3]

Although we were unable to implement quick-look versions of the 1˚ objective FSU fluxes, we continue to create an older version (the FSU2) 2˚ tropical Pacific Ocean wind (pseudo-stress) fields based on near-real time in-situ data. Quick-look 2˚ gridded pseudo-stress fields are produced at the beginning of each month using the previous month's GTS-transmitted data. In addition to the Pacific, COAPS continues to produce one-degree pseudo-stress fields for the tropical Indian Ocean using the method of Legler et al.[5]. Related research quality products exist through 2004 for the Pacific and 2003 for the Indian Ocean. We have not updated the FSU2 and Legler research products as we had anticipated switching to the near real time version of the FSU3 technique. This switch was delayed by the desire of the flux community to have an assessment of multiple flux products (including the FSU3), and the data quality and sampling issues we had to solve. We will push the quick-look FSU3 product forward to FY 2009. Both two-degree fields for the Pacific Ocean and one-degree fields for the Indian Ocean FSU winds are available at http://www.coaps.fsu.edu/ RVSMDC/SAC/index.shtml.

As part of our continued production of the FSU2 for the tropical Pacific Ocean, we now produce additional monthly graphics for inclusion into the on-line version of the NOAA Climate Diagnostics Bulletin (http://www.cpc.ncep.noaa.gov/products/CDB/).

2.4. Publish comparisons of FSU3 fluxes to other available in-situ, satellite, and blended flux products [Deliverable 4]

The research for this comparison is done. We have a draft of the paper, and are improving it prior to submission. The subtask of presenting the information at national and international meetings was completed. The discussions from these presentations indicate that most flux product users know very little about the qualities of the flux products they choose to use. It is clear that a well written comparison of the strengths and weaknesses of products would be of great service to a wide range of communities.

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[5] Legler, D. M, I. M. Navon, and J.J. O'Brien, 1989: Objective analysis of pseudostress over the Indian Ocean using a direct-minimization approach. *Mon. Wea. Rev*., **117,** 709-720.

2.5. Objective estimation of uncertainty in flux fields and related variables [Deliverable 5]

While we have completed key coding improvements, we have not found sufficient time to make much progress on this problem. The effective reduction in funding (level funding combined with increasing costs) has prevented us from working on the error analysis for our fields. We view this work as very important, but we lack the resources to continue that effort with our current budget. We are participating on other efforts that will help address key questions about the noise and practical resolution. That will be very helpful, but a spatially varying assessment is desired.

2.6. Production of satellite and NWP hybrid fluxes [Deliverable 6]

We produce equivalent neutral pseudostress fields, which can easily be used to determine surface stress. For isolated projects we produce hybrid NWP and satellite fluxes; however, we (in 2007) believed that there are substantial errors in the heat fluxes that should be addressed prior to public release of these products. In 2008, we investigated these biases, and found them to vary in space and time in a manner that would be difficult to correct and would cause large biases in even monthly averaged fluxes (subtask 1). We have investigated the importance of height adjustment and parameterization choice of the humidity values (subtask 2), and found that both considerations have physically significant impacts on the resulting fluxes. Mean differences due to parameterizations could be tens of Wm^{-2} for even mild conditions. We have also found that the differences due to the height adjustments have non-Gaussian distributions[6], which further complicates error analysis. In particular, we found that the biases associated with errors in episodic events (such as passage of atmospheric fronts; subtask 3) are quite large, even when considered as part of a monthly averaged flux. We therefore conclude that satellite and NWP hybrid result in biased fluxes, with the biases changing regionally and seasonally in a manner that is difficult or impossible to correct sufficiently for many applications. We have explored the possibility of combining observations of air temperature and humidity derived from satellite, and found some promise and the need for much more detailed assessment.

[6] Kara, A. B., A. J. Wallcraft, and **M. A. Bourassa**, 2008: Air-Sea Stability Effects on the 10m Winds Over the Global Ocean: Evaluations of Air-Sea Flux Algorithms. *J. Geophys. Res.,* **113**, C04009, doi:10.1029/2007JC004324.

3. PUBLICATIONS AND REPORTS

3.1.Refereed

Arguez, A. J. J. O'Brien, and S. R. Smith, 2008: Air Temperature Impacts over Eastern North America and Europe Associated with North Atlantic SST Variability. *International Journal of Climatology*, doi:10.1002/joc.1700, in press.

Kara, A. B., A. J. Wallcraft, C. N. Barron, E. J. Metzger, H. E. Hurlburt, and M. A. Bourassa, 2008: Accuracy of 10 m Wind Speeds from Satellites and NWP Products Near Land-Sea Boundaries. *Journal of Geophysical Research - Oceans*, *113*, C04009, doi:doi:10.1029/2007JC004324.

Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa, 2007: Connectivity between variability of the Apalachicola River flow and the biophysical oceanic properties of the northern West Florida Shelf. *Continental Shelf Research*, in press.

3.2. Technical reports and other publications

Moroni, D.F., 2008: A global and regional diagnostic comparison of air-sea flux parameterizations during episodic events, M.S. Thesis, 65 pp., Florida State University, Tallahassee, Florida, USA.

Smith, S. R., R. N. Maue, and M. A. Bourassa, 2008: 'Global Winds', State of the Climate in 2007, *Bulletin of the American Meteorological Society*, D. H. Levinson and J. H. Lawrimore, A. Arguez, H. J. Diamond, F. Fetterer, A. Horvitz, J. M. Levy, S32-S34, American Meteorological Society.

Bourassa, M. A., P. J Hughes and S. R. Smith, 2008: Surface Turbulent Flux Product Comparison, *FLUX NEWS*, *5*, 22-24.

Bourassa, M. A., D. Dukhovskoy, S. L. Morey, and J, J. O'Brien, 2007: Innovations in Modeling Gulf of Mexico Surface Turbulent Fluxes, *FLUX NEWS*, *3*, 9.

3.3. Conference proceedings/presentations

Bourassa, M. A., 2008: Remote Sensing of Ocean Surface Winds: Concepts and Applications, Univ. South Carolina, Feb., Columbia, South Carolina. *(Invited)*

Bourassa. M. A., 2007: Measuring surface turbulent stress from space. *2nd Oceanography Student Symposium*. Nov., Tallahassee, Florida. *(Invited)*

Morey, S. L, D. S. Dukhovskoy, and M. A. Bourassa, 2007: Connectivity between variability of the Apalachicola river flow and the biophysical oceanic properties of the Northern West Florida shelf . *2nd Oceanography Student Symposium*. Nov., Tallahassee, Florida. *(Invited)*

Moroni, D. F., and M. A. Bourassa, 2007: A global and regional comparison of air-sea flux parameterizations. Pacific Ocean Distributed Active Archive Center (PO.DAAC), Jet Propulsion Lab., Nov., Pasadena, CA. *(Invited)*

Bourassa, M. A., P. J. Hughes, S. R. Smith, and J. Rolph, 2008: Recent Air/Sea Flux Activities and FSU. *NOAA Climate Observations Division 6th Annual Review*, Sept., Silver Spring, MD.

Bourassa, M. A., L. Bucci, C. A. Clayson, C. Forgue, M. Onderlinde and B. Roberts, 2008: The Influences of Differing Temperature and Moisture Roughness Length Parameterizations on Height Adjustment and Turbulent Surface Fluxes. *Third JCOMM Workshop on Advances in Marine Climatology*, May, Gdynia, Poland.

Bourassa, M. A., L. Bucci, C. A. Clayson, C. Forgue, M. Onderlinde and B. Roberts, 2008: The Influences of Differing Temperature and Moisture Roughness Length Parameterizations on Height Adjustment and Turbulent Surface Fluxes. *2nd Joint GOSUD/SAMOS Workshop*, June, Seattle, Washington.

Hughes, P. J., M. A. Bourassa, S. R. Smith, 2008: Regional comparison of surface turbulent flux products. *Ocean Sciences 2008*, American Geophysical Union, March, Orlando, FL.

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Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa, 2008: Connectivity between variability of the Apalachicola River flow, episodic wind forcing, and the biophysical oceanic properties of the northern West Florida Shelf, *NOAA Climate Observations Division 6th Annual Review*, Sept., Silver Spring, MD.

Smith, S. R., M. A. Bourassa, S. D. Woodruff, S. J. Worley, E. C. Kent, and N. A. Rayner, 2008: A project to create bias-corrected marine climate observations from ICOADS. *Third JCOMM Workshop on Advances in Marine Climatology*, May, Gdynia, Poland.

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Hughes, P.J., M. A. Bourassa, and S. R. Smith, 2007: Regional comparison of surface turbulent flux products. *American Geophysical Union 2001 Fall Meeting*. Dec., San Francisco, California.